Seafloor Geomorphology, Gas & Fluid, and Slope Failure on the Southern Cascadia Continental Margin

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LONG TERM GOALS

Our long term goal is to understand the role of fluid flow and gas migration in the creation and modification of shelf and slope geomorphology and seafloor acoustic character. In addition, we are examining the interaction of tectonics, sediment accumulation and erosion in creating and modifying the morphology, stratal architecture and preservation potential of continental margins.

OBJECTIVES

We combine seafloor data and subsurface imaging to examine how hydrogeology, natural gas, eustasy, oceanographic forcing and tectonics interact and influence submarine geomorphology. The role of gas is evaluated by targeted sampling of the seafloor. Our objective is to determine the causes of anomalous seafloor bathymetry and reflectivity, and to relate reflectivity to gas migration, subsurface structure, and consolidation state.

APPROACH

The data sets we use are derived from a broad range of platforms. For seafloor data, we interpret EM-1000 multibeam bathymetry and backscatter, as well as towed side scan data. Additional data include a Hydrosweep multibeam survey collected adjacent to the main STRATAFORM area. For the subsurface, we are analyzing a nested suite of seismic data. Commercial multichannel seismic (MCS) reflection data provided by Amoco Corp provide the lowest frequency (deepest penetration and lowest resolution data) data. By combining our analyses of these data with STRATAFORM high resolution MCS data (Craig Fulthorpe, UTIG and Greg Mountain, LDEO) and even higher resolution Huntec (Mike Field, USGS) and EdgeTech CHIRP data (Neal Driscoll, WHOI), we examine structural and sedimentologic features at scales from several meters to kilometers sub-surface. These nested subsurface techniques are then combined with seafloor bathymetry and reflectivity data to determine the relationship between structure, gas, bathymetry and reflectivity. To groundtruth our hypotheses we utilize surface coring techniques to obtain samples for geochemical analysis. As part of the STRATAFORM program we also participated in a Monterey Bay Aquarium Research Institute (MBARI) sponsored ROV program to the Eel River Basin in August, 1997. We integrate these observations and analyses with the seafloor and subsurface data to analyze active vs. dormant processes, and to evaluate the role of fluid and/or gas migration in creating or modifying seafloor structures.

WORK COMPLETED

* We have completed analyses of head space gas samples from cores collected during the 1999 field season (in collaboration with T. Lorenson and K. Kvenvolden, USGS). Significant methane anomalies were encountered in a number of cores. Similar to our 1998 field program, numerous slope cores contained significant methane anomalies. In contrast to our previous programs, however, in 1999 we encountered significant anomalies in a number of cores from the shelf. These cores correspond to seismically opaque regions on CHIRP sub-bottom data.

* We participated in a July, 2000 R/V Thompson STRATAFORM cruise to the northern California study area to investigate the anomalous reflectivity on the shelf. We are collaborating with Neal Driscoll (WHOI) and Chris Summerfield (WHOI) on the interpretation of these data, specifically correlating observations of gas in the subsurface and on the seafloor (seismic and side scan) with head space gas analyses.

* We participated in the assembly of a STRATAFORM GIS. Larry Mayer (U. New Hampshire) led this task, and a CD-ROM has been distributed.

* Analysis of industry geophysical data on a Landmark workstation suggests that previously unknown high angle faults cross-cut the Eel River STRATAFORM field area, and that these faults are active. The relationship of these faults to sediment preservation potential and fluid seepage is under investigation.

* A detailed study of Huntec and hi-resolution MCS data is being carried out to evaluate the origin of anomalous seafloor features on the slope. These include an upper slope region of localized sediment accumulation and intervening erosion ("the Ridge and Swale zone") and the "Humboldt Slide. We interpret these features to represent upper slope deposition and erosion affected by sea level and tectonics.

RESULTS

Cores obtained from the shelf and slope contain significant concentrations of methane. These cores can be tied to sedimentological features, underlying structural culminations, and sea level. Compositional analysis of cores and ROV samples show that the gas in the Eel River Basin originates from both deep thermogenic and shallow biogenic sources. Previous ROV observations in the context of regional geophysical surveys led to our hypothesizing two different mechanisms for fluid expulsion: continuous along structure vs. episodic (and catastrophic) between structures.

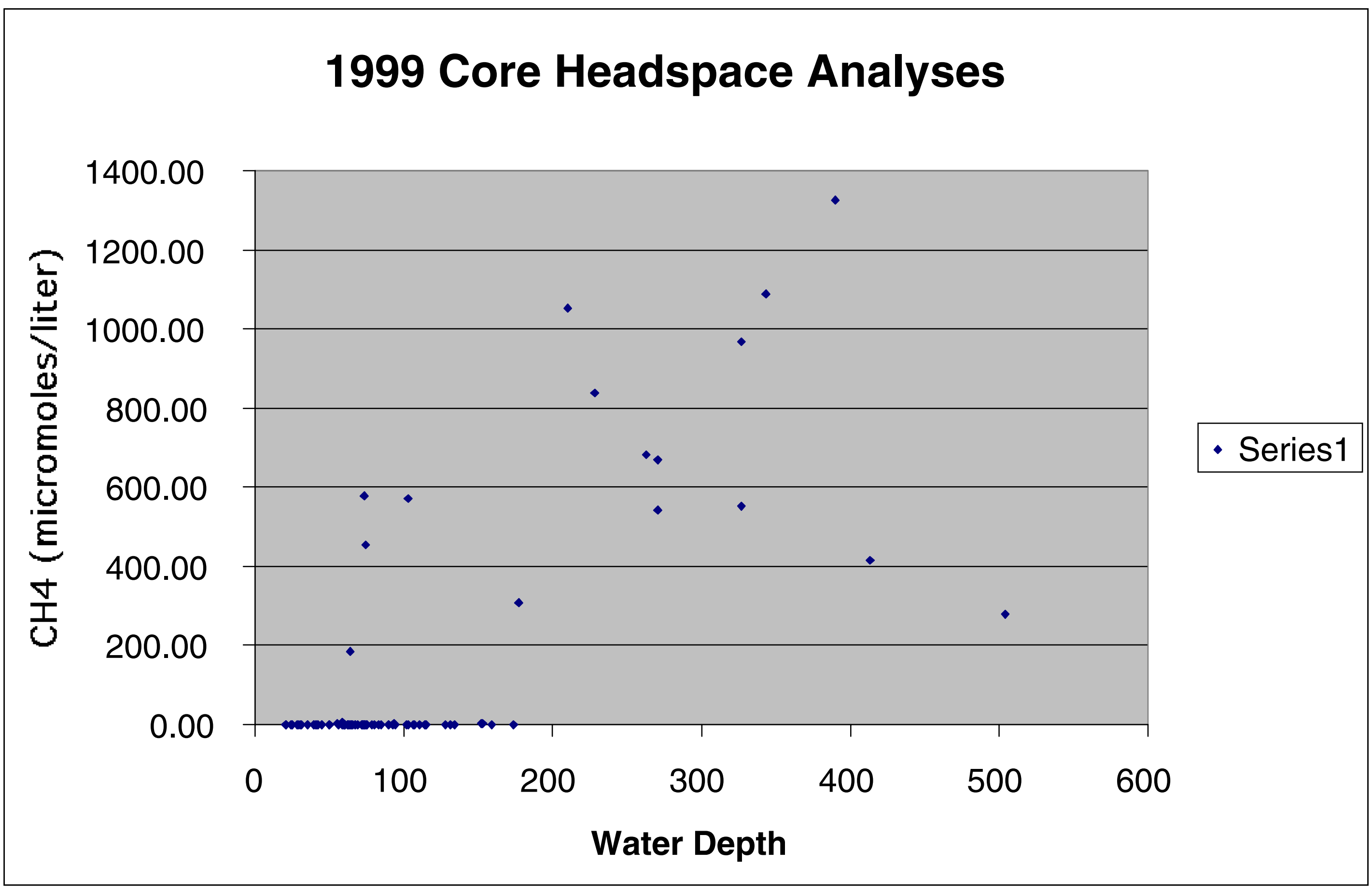
Geochemical Analyses

In our previous annual reports we have discussed authigenic carbonate samples (obtained via ROV) and headspace gas analyses from cores. ROV dives to the Little Salmon fault and Table Bluff anticline identified a large number of seeps, extensive authigenic carbonate, and gas bubbling out of the seafloor. These observations indicated that the high backscatter on the Little Salmon fault was related to the surface exposure of seep-related carbonate. ROV dives to a projected mud volcano on the shelf identified seeps and gas bubbling out of the seafloor.

Previously reported analysis of the Little Salmon Fault and Table Bluff Anticline authigenic carbonate samples indicated isotopic compositions of $\delta^{13}C$ of -15 $^{o}/oo$ to -30 $^{o}/oo$ and $\delta^{18}O$ of +4 and +6 (PDB). These compositions indicate precipitation from fluids with a strong thermogenic methane signature. Gas samples obtained with the ROV on the slope contained as much as 46,000 ppm methane, with minor but significant amounts of higher order hydrocarbons (gas and "head space" analyses conducted by T. Lorenson and K. Kvenvolden, USGS). Head space analyses provide an assessment of the constituents in a gas (C1, C2+, etc.) as well as a relative determination of gas concentrations. Absolute gas concentrations require pressurized sampling equipment to keep gas from coming out of solution during ascent through the water column.

Although the actual gas obtained at structural highs was predominantly methane with a mixed biogenic and thermogenic signature, the ethane in the gas was identical to samples of thermogenic gas obtained from wells in the on-shore Thompkins Hill gas. The Thompkins Hill field has produced 102 bcf of gas since 1937, with undiminished reserves estimated at 10 bcf even though current production equals 3.2 mcf/day.

In 1998, as part of the slope coring and Excalibur program, we obtained sediment samples from a number of sites on the shelf and slope. Numerous slope cores contained high gas concentrations, but none of the shelf cores showed anomalous gas. The shelf sites, however, were selected prior to the CHIRP and side scan programs which pinpointed shallow gas zones on the shelf. In 1999 we collected a number of cores from the slope and numerous cores on the shelf (see Graph, below).



On the slope, we focussed our efforts on two regions where we had inferred high sediment accumulation rates based upon our interpretation of the hi-res MCS and Huntec data: the “Ridge and Swale zone”, and the base of the “Humboldt Slide”. All of the cores from these sites showed very high gas concentrations, up to 1300 µml/l wet sediment (150,000 ppm). Cores showed parting and bubbles; no cores showed obvious gas hydrates.

On the shelf, the cores were being collected for the sedimentological studies of other ONR researchers (Nittrouer, Summerfield, Wheatcroft, Drake). The core locations were selected to provide broad coverage and even distribution. By analyzing all of the cores for headspace gas we were able to use this grid of samples to comprehensively test for the presence and distribution of shelf gas. Very high gas concentrations were found in 4 cores on the mid- to outer-shelf; all were collected in regions where CHIRP sub-bottom profiles showed evidence of subsurface gas. Anomalous shelf gas samples had up to 580 µmol/l wet sediment (55,000 ppm) gas. The apparent restriction of high shelf gas to a narrow bathymetric range (see Graph) begs the question as to what controls this band of shelf gas (discussed in Yun et al., 1999; see publications). In our on-going gas sampling and analysis program we are evaluating cores collected in July, 2000, again targeted with CHIRP sub-bottom profile data (Driscoll).

Indications of High Angle Faults on the Eel Shelf and Slope

Recently Janet Yun (UCSC Ph.D., 2000) undertook an integrated stratigraphic and structural analysis of multichannel seismic data both made available by industry and collected during STRATAFORM. Her work confirms previous maps showing that major folds swing from a northwesterly to a more east-west orientation through the Eel River Basin. Careful seismic stratigraphic mapping, however, shows that these folds are cut by high angle left-lateral faults that trend in an approximately east-west direction. The faults are oriented at high angles to the maximum principal stress directions inferred from the folds. These faults are interpreted to have low resolved shear stresses and are therefore "weak" faults. Seismic data shows evidence of gas migration up these faults to the seafloor. Submersible observations as well as industry "sniffer" data confirm the presence of gas at the sea floor along these faults. High pore pressures and associated fluid migration may explain the weak nature of the faults. These faults project into topographic lineaments onshore and may represent previously unrecognized geologic hazards.

IMPACT/IMPLICATIONS

Our investigation of seafloor morphology and reflectivity suggests that high resolution multibeam may be of use to the hydrocarbon and cable industries as both an exploration tool and a means of conducting cost-effective geohazard surveys. We have demonstrated an approach that identifies anomalous seafloor features and relates them to consolidation state and possibly to shallow gas. We have shown that high resolution multibeam data can be used to document seafloor seepages, and such seepages in petroleum environments provide direct samples of the fluids and hydrocarbons in a basin without exploration drilling; subsurface data can facilitate seep interpretation by relating surface exposures and seeps to the petroleum system responsible for the seepage. The same data used for targeting seeps can also used for geohazard analysis. Geohazards that can be identified include oversteepened slopes, regions of pre-existing slope failure, areas of excessive gas (indicated by pock marks and subsurface acoustic blanking), and mud volcanoes. High-resolution multibeam data can provide georeferenced data at a resolution similar to deep towed side scan, but at higher speeds and wider swath widths for greater efficiency. Multibeam data are most effective when combined with high resolution sub-bottom profiling and multichannel seismic data.

Our seismic data interpretations, ROV surveys, core sampling, and gas analysis surveys, show that gas migration may significantly affect seafloor backscatter intensity. We have shown that structural highs on this gas-rich margin are regions of long term gas expulsion, and that the gas currently leaking out of the seafloor is similar to thermogenic gas being produced from the correlative on shore Thompkins Hill field. Gas expulsion may be related to structural features, although the depth delimited band of gas on the Eel shelf argues for a stratigraphic or eustatic control. The bacterial oxidation of seafloor methane seeps leads to carbonate precipitation. This carbonate can armor the seafloor and significantly increase backscatter intensity. This phenomenon may be widespread on continental margins, leading to the prediction of increased backscatter on structural highs on any continental margin known to contain subsurface gas.

TRANSITIONS

By documenting tectonically uplifted regions where reflectors are compressed, our work will help define coring locations where reflectors can be sampled and extrapolated to the basin at large. This will aid in the interpretation of long-term sequence stratigraphic packages, and provide a methodology whereby numerous offset short cores can provide data on otherwise inaccessible deep reflectors.

Work on the tectonic history of the Eel Basin directly impacts STRATAFORM by contributing to the knowledge base about long-term ($> 10^5$ yr) strata preservation. Gas analyses provide quantitative ground-truthing of features seen in high resolution sub-bottom profiling.

RELATED PROJECTS

Our work on the interaction of gas, seafloor morphology and reflectivity is being carried out in close concert with the high resolution sub-bottom profiling surveys (CHIRP sweep-frequency sonars) conducted by Neal Driscoll (WHOI). We are also working with Larry Mayer (U. New Hampshire) in assessing methods to associate the presence and amount of gas in near-surface sediments with the azimuthal variation of seafloor backscatter.

We are also working on reflector correlations between the multiple seismic and sub-bottom profiling data sets (Mike Field, USGS; Casey Moore, UCSC). We are collaborating with Craig Fulthorpe (U. Texas) and Greg Mountain (LDEO) in integrating our studies of the commercial MCS data with their high resolution MCS data.

PUBLICATIONS

Orange, D.L., Yun, J., Maher, N., Barry, J., and Greene, G., (accepted) Tracking California Seafloor Seeps with Bathymetry, Backscatter and ROVs, Continental Shelf Research.

McAdoo, B.G., Pratson, L.F., and Orange, D.L. (accepted), Submarine landslide geomorphology, U.S. continental slope, Marine Geology.

Orange, D. and Stebbin, G. (1999) The Pocket Professor's Guide to Physics, Pocket Books (Simon and Schuster), New York, 135 pp. Release date: 8/99.

Orange, D.L., Greene, H.G., Reed, D., Martin, J.B., McHugh, C.M., Ryan, W.B.F., Maher, N., Stakes, D., and Barry, J. (1999), Widespread Fluid Expulsion on a Translational Continental Margin: Mud Volcanoes, Fault Zones, Headless Canyons, and Aquifers in Monterey Bay, California, *Geological Society of America Bulletin*, v. 111, p. 992-1009.

Stakes, D.S., Orange, D., Paduan, J.B., Salamy, K., and Maher, N., (1999), Origin of authigenic cold-seep carbonates from Monterey Bay. *Marine Geology*, v. 159, p. 93-109.

Orange, D.L., Angell. M. and Lapp, D., (1999) Applications of multibeam mapping to exploration and production: Detecting seeps, mapping geohazards, and managing data overload with GIS. *The Leading Edge*, v. 18, p. 495-501.

Goff, J.A., Orange, D.L., Mayer, L.A., and Hughes-Clarke, J.E., (1999) Detailed investigation of continental shelf morphology from a high resolution swath sonar survey over the Eel River Basin, northern California. *Marine Geology.* v. 154, p. 255-269.

Yun, J.W., Orange, D.L., and Field, M.E., (1999) Gas distribution in the Eel River Basin and its link to submarine geomorphology. *Marine Geology.* v. 154, p. 357-368.

Orange, D.L., (1999) Tectonics, Sedimentation, and Erosion in Northern California: Submarine Geomorphology and Sediment Preservation Potential as a Result of Three Competing Forces, *Marine Geology.* v. 154, p. 369-382.

Lorenson, T.D., Orange, D.L., Brewer, P.G., Davisson, M.L., McLaughlin, R.J., Kvenvolden, K.A., and Martin, J.B., 1998, Comparison of offshore and onshore gas occurrences, Eel River Basin, northern California: U.S. Geological Survey Open-File Report 98-781, 1 sheet

ABSTRACTS

Orange, D.L., and Teas, P., (2000) Examining enigmatic slope deposits, NSF Workshop on the prediction of underwater landslide and slump occurrence and tsunami hazard off of southern California. March 10-11, Los Angeles, CA.

Lorenson, T.D., Magoon, L.B., and Kvenvolden, K.A., Davisson, M.L., Orange, D.L., and Brewer, P.G., Martin, J.B., Lillis, P.D., (1999) The Ethane Connection Between Gas Hydrate and Gas Seeps in the Cape Mendocino-Eel River Basin Area, Offshore and Onshore Northwestern California, to be presented at the AAPG Hedberg Conference, June 6-10, Durango, Colorado.

Orange, D.L., Angell. M. and Lapp, D., (1999) Using Seafloor Mapping (Bathymetry and Backscatter) and High-Resolution Sub-Bottom Profiling for both Exploration and Production: Detecting Seeps, Mapping Geohazards, and Managing Data Overload with GIS, Offshore Technology Conference, Houston, Texas, 3-6 May 1999, p. 469.

Lorenson, T. D., Magoon, L.B., Kvenvolden, K.A., Davisson, M.L., Orange, D.L., Brewer, P.G., and Martin, J.B., (1999) Similarity of Gases in the Cape Mendocino-Eel River Basin Area, Offshore and Onshore Northwestern California, Pacific Section AAPG, Seaside, California, p. 35-36.

Martin, J.B., Day, S., Wheat, C.G., Plant, J., Orange, D.L., and Lorenson, T.L. (1999) Sedimentary Record of Cold Seeps, Pacific Section AAPG, Seaside, California, p. 37.

Orange, D.L., Yun, J., Greene, G., Lorenson, T., Kvenvolden, K., Wheat, G., Martin, J., Campbell, K., Barry, J., and Maher, N., (1999) California Cold Seeps Past and Present: Monterey Bay, the Eel River Basin, and Inland Paleo-Seeps, Pacific Section AAPG, Seaside, California, p. 39-40.

Yun, J., Field, M.E., Foland, S.S., Orange, D.L., and Moore, J.C. (1999) Gas Occurrence from the Subsurface to the Water Column: An Integrated Study in the Offshore Eel River Basin, CA, Pacific Section AAPG, Seaside, California, p. 47.

Orange, D.L., Angell. M. and Lapp, D., (1999) Seafloor Mapping for Exploration and Production: Seep Detection, Geohazards, Decreased Cycle Time, and GIS to Manage it All, American Association of Petroleum Geologists.

Orange, D., Field, M., Gardner, J., Driscoll, N., and Mayer, L. (1998) High resolution seismic images of stacked transgressive sequences proximal to an active fault on the northern California margin, *EOS (Transactions, American Geophysical Union)*, v. 79, p. F497.

Driscoll, N., Orange, D., Yun, J., Fonseca, L., and Mayer, L. (1998) High resolution side-scan and seismic images of landslides on the northern California continental shelf, *EOS (Transactions, American Geophysical Union)*, v. 79, p. F811.

Orange, D. L., Yun, J., and Maher, N. (1998) Using high resolution multibeam (bathymetry and reflectivity) and ROV surveys to track fluid and gas seeps on the northern California shelf and slope, *5th International Conference on Shallow Gas, Bologna, Italy, p. 82.*

Yun, J.W. (1998) Tectonic controls on the formation, deformation, and erosion of strata in the Eel River basin, California. SEPM-IAS Research Conference on Strata and Sequences on Shelves and Slopes, Sicily, Italy.

Yun, J.W., and Foland, S.S. (1998) Varying structural and stratigraphic character offshore northern California. *EOS (Transactions, American Geophysical Union),* v. 79